AN ANALYSIS OF WATER MANAGEMENT FOR A PEM FUEL CELL SYSTEM IN AUTOMOTIVE DRIVE CYCLES

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ABSTRACT

Low-temperature operation of a Proton Exchange Membrane (PEM) fuel cell system requires humidification of the membrane. The amount of water produced electrochemically within the fuel cell system is directly related to the system power output. In a vehicular application where the power output may vary substantially over time, it is critical that water management be addressed in the fuel cell and vehicle system design. This paper introduces the integration of a detailed fuel cell system model within a hybrid electric vehicle system model. The newly integrated models provide the capability to better understand the impacts of a variety of fuel cell and vehicle design parameters on overall system performance. Ultimately, coupling these models leads to system optimization and increased vehicle efficiency. This paper presents the initial results of a parametric study to quantify the impacts of condenser size and cathode inlet relative humidity on system water balance under realistic drive cycles in a fuel cell hybrid electric sport utility vehicle. The vehicle simulations included operation under both hot and ambient start conditions. The study results demonstrate that ambient start or aggressive drive cycles require larger condensers or water reservoirs to maintain a neutral water balance than either hot start or less aggressive drive cycles.

INTRODUCTION

Fuel cell systems have the potential to significantly increase vehicle energy efficiency and reduce regulated emissions in transportation applications. The performance of the fuel cell governs the efficiency and performance of the system. Furthermore, the performance of the proton exchange membrane (PEM) fuel cell depends on multiple operating parameters including temperature, pressure, and relative humidity. The parasitic loads due to the balance of plant, which provide the desired operating conditions, have a significant influence on the overall system efficiency. Therefore, temperature, pressure, and water management affect the overall fuel cell system performance. This paper focuses on fuel cell system water management in the context of vehicle transient power requirements.

The polymer membrane in the fuel cell requires a continuous supply of water to hydrate the membrane and maintain proton conductivity. Typically, the membrane water content is managed by humidification of the inlet gas streams. A careful balance of water is necessary because too much water will ‘flood’ the membrane, blocking the transport paths of the protons, whereas too little water will create ‘hot spots’ and reduced conductivity. Both scenarios contribute to reduced performance and lead to potential failure of the fuel cell.

The amount of water to humidify the inlet gases and maintain membrane performance can be significant. Water is also produced at the cathode as a product of the electrochemical reaction. The cathode and anode exhaust streams typically exit saturated at the fuel cell stack operating temperature. Recovery of the water vapor exiting the fuel cell is critical to supply the inlet gas humidification needs and maintain sustainability. A condenser is normally used to recover this water from the exit stream. The difference between the water recovered by the condenser and that required to humidify the inlet gases over time is defined as the water balance. A positive water balance means that there will be a water surplus, whereas a negative water balance leads to a water deficit. A neutral water balance over time is desirable and necessary in order to provide a self-sustaining fuel cell system.

Today’s PEM fuel cell systems are designed to operate in the range of ambient pressure (100 kPa) to 300 kPa and 60-80 ºC. Higher temperatures and higher pressures typically

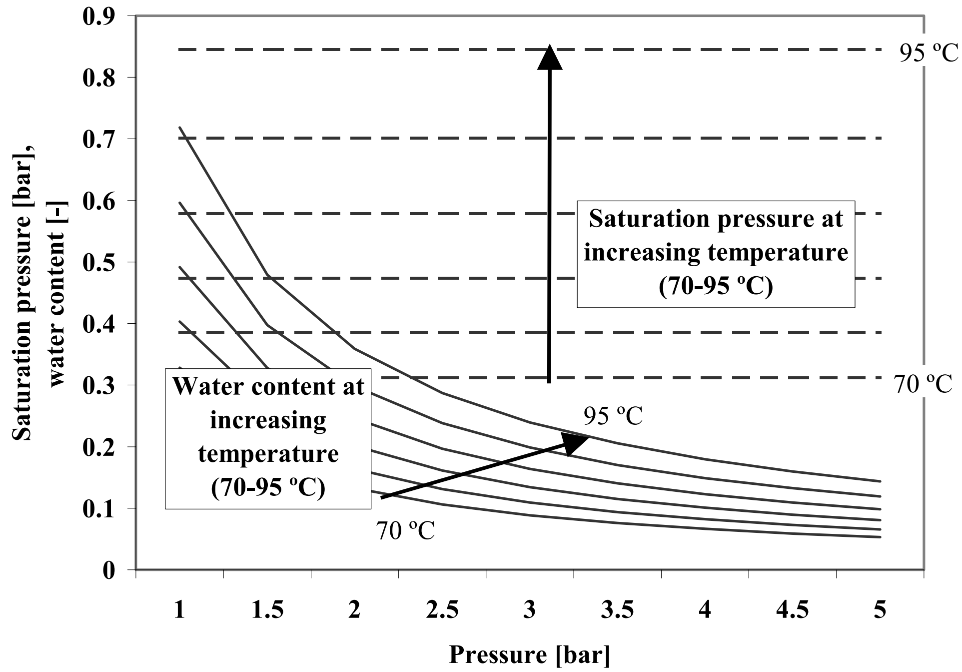

Figure 1. The influence of pressure and temperature on saturation pressure and water content

lead to greater fuel cell power density. However, as shown in Figure 1, at elevated temperature, the saturation pressure of the gas increases; hence, the amount of water to be transported along with the inlet gases increases to provide the same relative humidity level. Conversely, at elevated operating pressure, the water requirements are reduced. However, pressurization of the system increases the parasitic loads and reduces the system efficiency. It is clear that inlet temperature and pressure will contribute to the water management issues. This study considers the impacts of varying the target relative humidity of the inlet gases on the overall water balance.

At the system outlet, sizing of the condenser will be critical to recover sufficient water to serve the needs at the inlet. However, the condenser size should be minimized to satisfy system packaging, weight, cost, and volume constraints. In this study, the variation in water balance over typical drive cycles in a fuel cell hybrid vehicle is reviewed with respect to the sizing of the condenser.

APPROACH

The impact of fuel cell system parameters on vehicle performance is studied using ADVISOR™ (**AD**vanced **V**eh**I**cle **S**imulat**OR**), a vehicle simulation software tool developed by the National Renewable Energy Laboratory (NREL).

ADVISOR™, created in the MATLAB/Simulink environment, has graphical blocks that are interlinked to form various vehicle systems. It combines advanced engines, motors, generators, transmissions, batteries, ultracapacitors, fuel cells, and accessories to create conventional, electric, hybrid electric, and fuel cell vehicle configurations. These configurations are then evaluated over standard drive cycles or through pre-defined test procedures to determine fuel economy and performance characteristics (Markel et al., 2002). Recently, two new detailed PEM fuel cell system models were integrated into ADVISOR™ to enable better understanding of the interaction between the fuel cell system level parameters and the vehicle level parameters. The fuel cell models were discussed in detail by Haraldsson and Wipke (2002).

The fuel cell hybrid vehicle was simulated over several drive cycles. The drive cycles considered include:

- UDDS – Urban Dynamometer Driving Schedule, represents typical urban driving, part of U.S. EPA Federal Test Procedure
- US06 – high-speed, high-acceleration-rate driving profile to be included in U.S. EPA Supplemental Federal Test Procedure (SFTP)

All drive cycle results are presented as “state of charge (SOC) balanced”, meaning that the difference between the battery pack SOC at the end of the cycle is not significantly different than the battery pack SOC at the beginning of the cycle. This is necessary to provide comparable fuel economy results.

Vehicle assumptions

A mid-size sport utility vehicle (SUV), similar to a Jeep Grand Cherokee, was used as the platform for this study. The vehicle assumptions shown in Table 1 have been used in several previous optimization studies (Markel et al., 2002a). In this study, the NiMH battery pack used in previous studies has been replaced with a 12 Ah Li-Ion battery pack. Table 2 summarizes the hybrid component characteristics.

Table 1. Vehicle assumptions

Vehicle Type	Rear-wheel-drive mid-size SUV
Baseline conventional vehicle mass [kg]	1788
Fuel cell hybrid vehicle glider mass (no powertrain) [kg]	1202
Fuel cell hybrid vehicle mass (with powertrain) [kg]	1825
Wheel radius [m]	0.343
Rolling resistance [-]	0.012
Frontal area [m^2]	2.66
Coefficient of aero. drag [-]	0.44

Table 2. Component characteristics

Components	Description
Fuel cell system	50 kWe pressurized fuel cell system, based on Virginia Tech model
Motor/controller	117 kW AC induction motor/inverter
Energy storage system	12 Ah Li-ion battery pack

The hybrid vehicle control strategy for this study was designed such that the fuel cell system remains on at all times unless the ignition key is turned off. Implementation of a fuel cell system with full start/stop capability is still several years away, so this assumption is meant to portray a practical system in the context of today's technology. The battery pack in this system is used for power-assist and regenerative braking energy recovery during drive cycles. The chosen strategy impacts the power demands on the fuel cell system and thus the water balance. In future studies, the control strategy will be varied to quantify its influence on the water management.

Fuel cell system characteristics

For the simulations, a fuel cell system model developed by Virginia Tech in collaboration with NREL (the VT model) was applied (Gurski and Nelson, 2002). The VT model is a parametric model that accounts for the thermal management and water balance in the system. It has a transient finite difference thermal model that captures cold-start effects on vehicle performance.

Figure 2 shows a schematic of the model. The PEM fuel cell system operates on pure hydrogen. The inlet gases are humidified in separate humidifiers. The stack outlet gases are assumed to be fully saturated (i.e., RH = 100%). The cathode exhaust is cooled in the condenser where part of its water content is condensed out and recovered for reuse in the humidification process. The system operating pressure varies as a function of the fuel cell load. Table 3 summarizes the major operating parameters of the VT model.

Table 3. Fuel cell system parameters for the VT model

Parameters [units]	Value
Net power output [kW]	50
Fuel cell area [cm^2]	678
Number of cells in stack [-]	210
Minimum cell voltage [V]	0.6
Stoichiometric coefficient (air)	2.5
System efficiency, rated power [%]	35
Peak system efficiency [%]	57.5

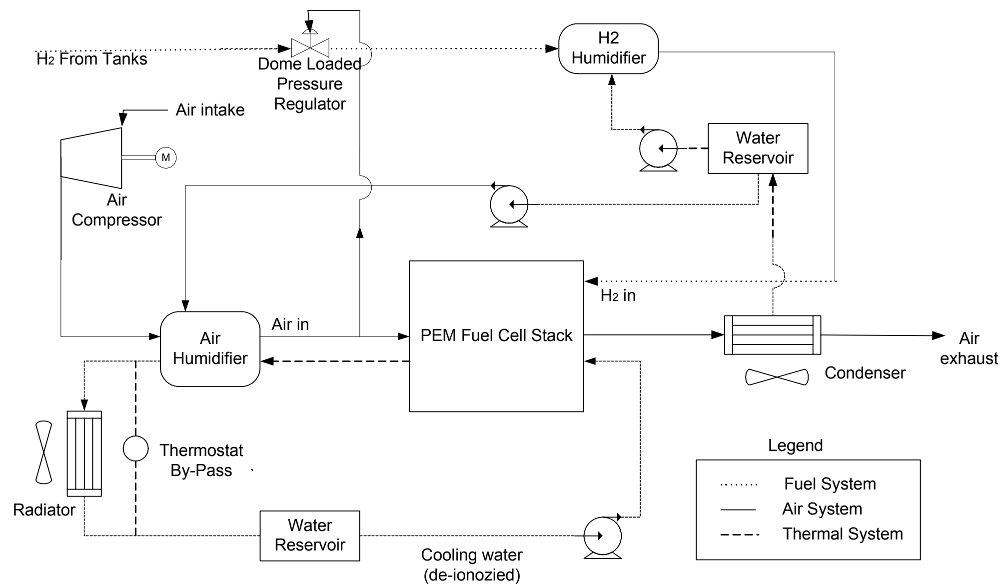

Figure 2. Schematic of the Virginia Tech fuel cell system model (VT model)

RESULTS AND DISCUSSION

The system parameters of condenser frontal area and the inlet relative humidity of the cathode gas stream were varied to investigate their impact on the fuel cell system water balance and vehicle performance. This was done for several drive cycles under both ambient and hot-start conditions in a hybrid vehicle scenario. Table 4 summarizes the parameter ranges considered in this study.

Table 4. System parameters and range of value

Parameter	Range
Condenser frontal area [m^2]	0.35-0.65
Cathode inlet relative humidity [-]	0.3-0.8

Figure 3 shows the water balance at ambient and hot starts in the US06 cycle for the large condenser case. When starting from ambient conditions, it takes time for the fuel cell system to reach the operating temperature. During this time, the temperature of the thermal masses of the fuel cell stack and the water reservoir are rising, modeled here as lumped capacitances. This heating delay results in different water balances for the two cases. The hot-start case has a positive water balance for the entire cycle, i.e., the water needed for humidification is provided by condensation of the exhaust gases from the fuel cell stack. In comparison, the ambient start case takes more than 200 seconds to achieve a positive water balance.

The two diagrams in the middle of Figure 3 display how different water flows under hot-start conditions are affected by the drive cycle power demand. Water enters the system via the inlet cathode and anode gas streams. Water is also generated at the cathode. The difference between the water in the cathode outlet and the cathode inlet is approximately equal to the water generated electrochemically in the stack.

During the drive cycle, heat is generated in the stack and is removed via the coolant stream, the exit cathode, or the anode gas flows; otherwise it raises the temperature of the stack. Under hot-start conditions, the condenser is effective at dissipating the heat of the exit gas flows and recovers a significant amount of water. However, under ambient start conditions it is more difficult to reject the heat and recover the water due to a small temperature difference between the exit air and ambient conditions.

Comparisons of the water balance in two drive cycles are shown in Figure 4. Table 5 shows an overview of the performance of the fuel cell hybrid SUV and its fuel cell system. In Figure 4 and Table 5, the cathode inlet humidity is set to 80%, while the condenser frontal area is varied. The water accumulated during the drive cycle has been normalized by the drive cycle distance to facilitate comparison.

The amount of water accumulated for the ambient start case is less than the hot-start case. As discussed above, this is because less heat is rejected in the condenser. Increasing the heat transferred from the condenser to the environment will allow more water in the cathode exhaust to condense, and the water balance will improve. This can be accomplished by increasing the condenser frontal area. It is desirable to find an ideal tradeoff between condenser frontal area and water balance. When the demands of a more strenuous drive cycle like the US06 are considered, it is clear that the water balance is even more sensitive to condenser frontal area. At the extreme, under ambient start conditions on the US06 cycle, assuming a condenser frontal area of 0.35 m^2, a significant negative water balance results and would necessitate a large water reservoir.

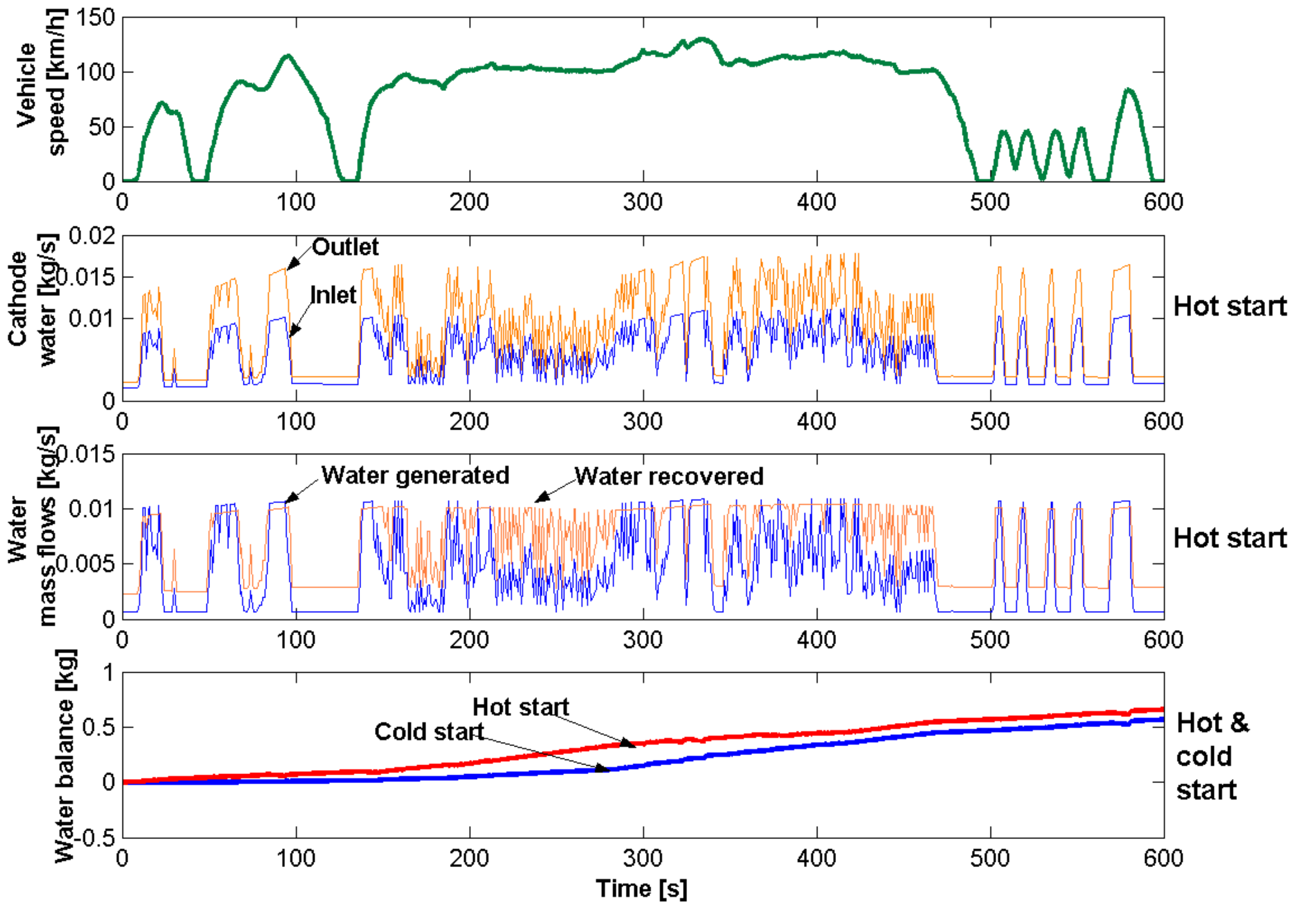

Figure 3. Example of the water balance of a fuel cell hybrid SUV in the US06 drive cycle under ambient and hot-start conditions ($RH_{cathode} = RH_{anode} = 80\%$, Condenser frontal area = 0.65 m^2)

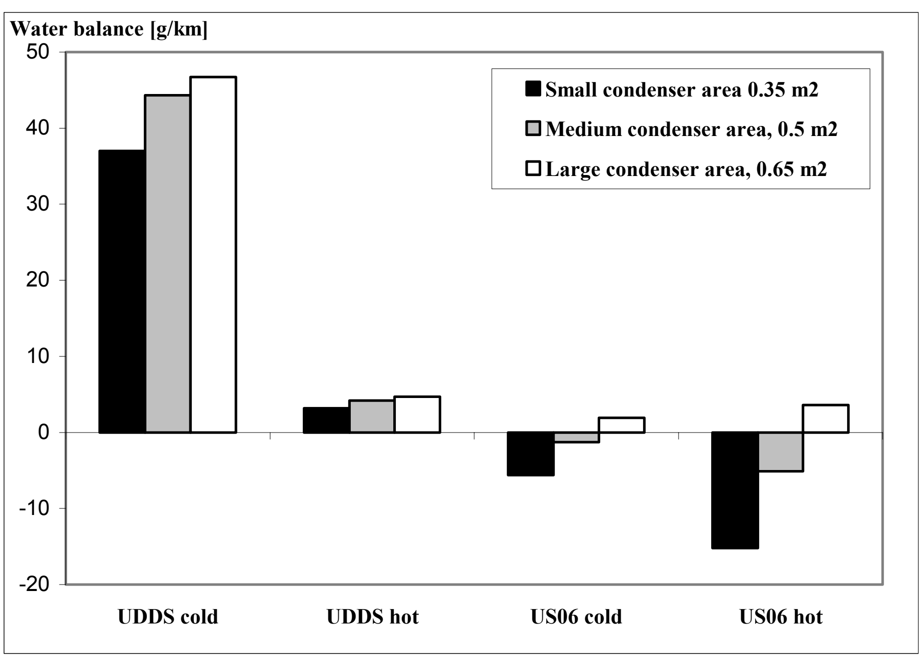

Figure 4. Water accumulation over drive cycles for ambient (cold) and hot start cases

Table 5. System performance based on average values for ambient and hot-start conditions (condenser area = 0.65 m^2, $RH_{cathode} = RH_{anode}$ = 80%)

Cycle	UDDS		US06	
Initial start condition	Ambient	Hot	Ambient	Hot
Fuel consumption (gasoline equivalent) [L/100 km]	4.45	4.3	8.2	8.1
FC system efficiency [-]	0.53	0.55	0.42	0.43
Net FC system power [kW]	4.5	5.6	17.4	17.5
FC stack efficiency [-]	0.55	0.66	0.57	0.6
FC stack heat [kW]	3.9	4.3	27	26
Condenser heat [kW]	1.4	4.7	8.3	14

Although a given drive cycle's average water balance may be positive, a negative water balance may exist during some parts of the cycle leading to the need of a water reservoir. A negative water balance was observed in the ambient UDDS cycle case but has an overall positive water balance. A negative water balance occurs until the system approaches normal operating temperature. Under the current system assumptions, the hot-start scenarios produce a positive water balance throughout the drive cycle.

Closely linked to water management is heat management of the system. To avoid the need for external heating and to reduce the heat load of the radiator, a careful match between heat sources and sinks is necessary. For example, humidification of inlet gases requires energy that must be supplied from within the system. The energy can be provided by the fuel cell stack cooling circuit or by an extra electrical heating device. Additional analysis of the heat and water management systems for fuel cell hybrid vehicles should be completed with an emphasis on overall system optimization with respect to the vehicle drive cycle.

CONCLUSIONS

This study demonstrates an approach to understanding water management issues of a fuel cell system in a hybrid electric vehicle architecture. A parametric analysis was performed to quantify the impacts of condenser sizing on water management of a fuel cell system in a hybrid electric SUV. ADVISOR™, a vehicle simulation software tool with a newly integrated detailed fuel cell system model developed by Virginia Tech and NREL, was used to understand the impacts of fuel cell system characteristics on water management over realistic drive cycles. Maintaining a net zero water balance during operation is desirable, and obtaining such a balance is directly related to operating parameters (e.g., temperature, pressure, and relative humidity) and system design parameters such as condenser size. The drive cycle and the system design parameters interact to influence the overall system water balance. A large condenser will be necessary to maintain a positive water balance for both ambient and hot start conditions for aggressive drive cycles (e.g., US06). Conversely, if a small condenser is used a large water reservoir will be needed to satisfy the fuel cell system water requirements under these operating conditions. The water balance during the urban drive cycle was occasionally negative but regained a positive balance by the end of the drive cycle. It is important to study the heat and water interactions within the fuel cell system for actual vehicle drive cycle requirements. It is also important to match the need for neutral water balance with the need for a compact and lightweight fuel cell system in the context of a hybrid electric vehicle.

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